Electrical Power and Energy Systems 109 (2019) 513–525

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Regional coordination in ancillary services: An innovative study for secondary control in the Iberian electrical system

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ARTICLE INFO

Keywords:
Ancillary services
Electrical market
Economical analysis
Interconnection
System operator, Regional Imbalance

ABSTRACT

The decarbonization of the electrical system (ES) is an inevitable truth. Thus, many economies that share concerns about climate change, invest in renewable sources to help contain the global warming. However, the massive integration of these renewable sources, which brings more intermittency and volatility, together with the natural variation of consumption, pose greater challenges that should be mitigated with adequate tools, as offered by a liberalized and organized electrical market. To help cost reduction in a market environment, the coordination between different Transmission System Operators (TSOs) is of utmost importance. The objective of this work is to provide a framework analysis for the sharing of ancillary services (AS) in the context of the Iberian ES, in particular a techno-economic analysis for the secondary reserve (SR) control. The SR control is fundamental to correct load variations and help stabilize the ES where the TSOs are inserted. To this end, the main goal is to control the regional imbalance of the Iberian Peninsula, in a coordinated way, with a minimization of costs. The results show that it is possible to generate synergies in 45% of the market periods and an average profit of 3.4 M€ per year. There are enough reasons to implement the coordination procedures between the Iberian TSOs in order to manage their own SRs in a profitable and reliable way, and to become more competitive when exchanging with other European TSOs.

1. Introduction

Electrical markets worldwide are a crucial structure of the electrical system (ES) even considering their differences and the players' various responsibilities, and moreover, when excluding their differences and locations, wholesale electrical markets are employed and joined considering the regional electrical markets. The collaboration starts through the cross-border high-voltage lines where the electricity interchanges may help to reduce the imbalances resulting from the demand and consumption equilibrium, or to increase the integration of renewable production, or even to aide in the enhancement of electrical security and reliability [1].

One of the biggest challenges in ESs is the way in which to deal with the high share of intermittent integration from renewable production, and with the social consumption behavior, considering the importance of reducing the pollutant emission rates, and coping with the regional targets. However, the increased variability and the intermittent nature effects in the net load require that conventional production fulfills the demanding operational flexibility requirements, where the balancing mechanism comes into operation and, as a consequence, the operational costs increases [2]. Innovative tools, e.g., for demand response or other forecasting features, and scheduling mechanisms usually help the Transmission System Operators (TSOs) in Europe to have a good approximation of how to deal with the unbalancing periods and to use the reserves, interchanging electricity between the cross-border TSOs [1,3].

Widespread efforts shown by the scientific community provide

Abbreviations: aFRR, Automatic Frequency Restoration Reserve; AGC, Automatic Generation Control; AS, Ancillary Services; BA, Balance Areas; EEG, European Electrical Grid; ES, Electrical System; FPP, French Power Plants; IES, Iberian Electrical System; ISO, Independent System Operator; MES, Morocco Electrical System; PES, Portuguese Electrical System; PRR, Primary Regulation Reserve; PSO, Portuguese System Operator; REE, *Red Eléctrica de España* (Spanish TSO); REN, *Redes Energéticas Nacionais* (Portuguese TSO); RR, Regulating Reserve; SDR, Secondary Downward Regulation; SES, Spanish Electrical System; SR, Secondary Reserve; SUR, Secondary Upward Regulation; TDR, Tertiary Downward Regulation; TSO, Transmission System Operator; TUR, Tertiary Upward Regulation

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https://doi.org/10.1016/j.ijepes.2019.02.027
Received 23 October 2018; Received in revised form 24 January 2019; Accepted 18 February 2019
Available online 27 February 2019
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adequate solutions to the ES in order to improve its flexibility. For instance, in [4] it was proved that nuclear energy may work together with renewable energy in order to increase electrical flexibility, instead of its normal operation as a base load system, changing the power output overtime, providing the necessary frequency regulation and operating reserves, and at the same time helping the ES to cope with the low-carbon paradigm.

Moreover, more business models considering the combination of renewables' integration with other mechanisms show that it is possible to enrich the ES with more advanced technologies [5]. However, the efforts to harmonize the balancing capacity between different TSOs and the possible share of their balancing mechanism may help the ESs, like the Iberian ES, to cope with the European requirements and be more competitive and active when compared to the overall European transmission system, in the near future, fulfilling the latest European directives for the energy sector and the environmental targets [6].

Previous research has shown, for instance, in [7] the possibility of cooperation between ancillary services (AS) in the continental Europe sphere, especially in voltage control. In [8] a detailed technical description and an overview of AS in Spain were elaborated. In [9] the technical and economic aspects, considering several types of AS, such as voltage control, frequency regulation, and system restoration, around the globe (from Australia to Nordic countries) were presented.

In [10] a comprehensive study of the issues in China related to AS was presented. In [11] a review was focused on the North American ES, showing the design of the AS markets and examining the methods by which the AS are procured, by highlighting the procurement practices at a number of different Independent System Operators (ISO). In [12] a review of reserve types and dispatching methods was elaborated, and different approaches were discussed. In [13] an overview of the markets for the Nordic countries' cross borders AS was elaborated. An economic evaluation of tertiary exchange in the Iberian ES was elaborated in [14]. A review of flexibility products and markets was elaborated in [15].

The present work focuses on the cross-border cooperation between TSOs in the Iberian market, with the focus on reducing the operational costs, by sharing and optimizing AS as the Secondary Reserve (SR) in the Iberian Peninsula. In detail, the objective of this work is to provide a framework analysis for the sharing of AS in the context of the Iberian Electrical System (IES), in particular, a techno-economic analysis of sharing SR control, or (*automatic Frequency Restoration Reserve* - aFRR). To this end, the goal is the control of the imbalance, in both ESs, with a minimization of costs.

The main innovative contributions of this work are as follows:

(1) A detailed analysis of the IES's secondary energy mobilization in the recent past;
(2) Identification of the market periods where cooperation could be possible between both IES;
(3) Calculation of the potential profits of secondary sharing cooperation. To this end, the applicability and the proposed method for calculation of the potential profits are also discussed.

This manuscript is organized in the following sections: Section 2 describes the perspectives of AS, under the Iberian perspective, showing the scope, its importance, the challenges and the new challenges regarding the higher integration of renewable generation; Section 3 describes and quantifies the SR control considering the daily market analysis and the trimester analysis; Section 4 presents the identification and the analysis of the potential Iberian TSOs synergies. In this section is also provided the mathematical formulation, the daily and trimester analysis considering the Iberian TSOs synergies, and the result analysis from the Iberian TSOs synergies; finally, in Section 5, the main conclusions of this work are addressed.

2. Perspective for ancillary services: the Iberian reality

2.1. Scope, importance and new challenges

AS are crucial for the good performance of ESs. The main functions of AS are to help the grid operators to keep a reliable ES as the proper flow and direction of electricity, addressing the imbalances between supply and demand, and helping the system recover after a power system incident. To fulfill the missions described above, the European Electrical Grid (EEG), composed of 24 TSOs, needs to maintain its balance [16]. To promote these objectives, three types of reserves can accomplish this goal:

- Primary Reserve;
- Secondary Reserve (or aFRR);
- Tertiary Reserve (or Regulating Reserve - RR).

The Primary Regulation Reserve (PRR) is related to the action of the turbine speed regulator due to a shift of the ES's frequency, with the aim of adjusting the power of the generator group. The resulting power variation should take place within 15 s after the onset of the disruptions which cause frequency shifts of less than 100 mHz, and linearly between 15 and 30 s for frequency shifts of 100–200 mHz. The aim of the aFRR is to control the shifts in the programmed interconnection, to collaborate in maintaining the joint frequency, or, in the event of islanded operation, to control the system's frequency shifting considering the nominal frequency [17,18].

In the case of the RR, it represents the possibility of power variation (positive or negative) in the system groups which can be used within the current programming operation period [19,20]. Whenever the previewed production in the last programmed load is different from the demand forecast, a mobilization or demobilization of production/consumption in the Balance Areas (BA) will be instructed in order to balance the production with the referred demand, meeting the minimum reserve requirements [9,21,22].

In scenarios with significant renewable energy, additional AS may be required to manage the increased variability and/or uncertainty [23]. It is necessary to assess the effectiveness of the wind control methods used to address the economic issues associated with a higher penetration of wind or other renewables [24]. However, the evolution of electricity markets combined with technology developments allows the participation of renewable production in AS, in the day-ahead market [25].

2.2. Iberian electrical system

The Iberian Peninsula has two countries, and the respective TSOs that ensure the operation of the electrical grid of both ESs are REN - *Redes Energéticas Nacionais* as the Portuguese TSO, and REE - *Red Electrica de España* as the Spanish TSO. A brief description related of the years 2015 and 2016, of both ESs, is available in Table 1 [20,26,27]:

From the analysis of Table 1, which summarizes the main data about the production and the installed electrical capacity in both electrical systems, the Spanish Electrical System (SES) is approximately five times bigger than the Portuguese Electrical System (PES). In the IES, the SES represents 80% and the PES the remaining 20% from the

Table 1
Description of the Iberian ESs.

	Portugal		Spain	
	2015	2016	2015	2016
Consumption (TWh)	49.00	49.30	248.40	250.00
Peak Demand (GW)	8.62	8.14	40.70	40.50
Install Capacity (GW)	18.56	19.52	101.00	100.00

Table 2
Transacted Energy between TSOs - Portugal (PT) Spain (SP), France (FR) and Morocco (MO).

Year (Energy)	FR → SP	SP → FR	MO → SP	SP → MO	PT → SP	SP → PT
2015 (GWh)	9,277	1811	3	5016	2240	4441
2016 (GWh)	13,268	5241	0	5029	7020	1796

data provided for the peninsular system (the insular systems that belong to each TSO are not included in this analysis). Regarding the interconnection of ESs, the correlation is more difficult to define between both electrical systems for some reasons.

The first one is the number of interconnections due to the geographical situation: Portugal is the most western country in Europe and only has electrical interconnections with Spain. Moreover, the SES has electrical interconnections with Portugal, Morocco and France. Table 2 shows the main numbers of both electrical countries, from the day-ahead market results [20,27].

In 2015, the PES was an importer trend in the annual balance of energy interconnection, and in 2016 it was an exporter trend. Concerning the Spanish TSO, the interconnection balance has the inverse trend. In 2015 the balance was in the export direction, while in 2016 it was in the import direction. In the Portuguese case, the deductions are easy to make because the only existing commercial partner is the SES: the balance is exclusive with Spain. In the SES, as mentioned above, there are electrical interconnections with three countries.

To observe the trend, it is necessary to observe the detailed behavior from each TSO. In Table 2 it is possible to observe this information (final market results, including the intraday market results) [28].

3. Description and quantification of secondary reserve control

As mentioned previously, the AS are crucial for the operation of ESs. Tables 3 and 4 show the results of the annual mobilization and the average price of both TSOs, during the years 2015 and 2016, respectively.

It is important to note that an adequate balance of the ESs results from the combination/management between SR and RR. This process and operation is managed by each country's system operator. First of all, a general (macro) analysis of the obtained results is made, containing some previous remarks and findings. Then, a more detailed analysis is carried out, focused exclusively on SR control, arranging the results in a different manner to enable two different types of reflections:

- A daily analysis (in the short-term perspective), where it is possible to understand the behavior and the characteristics of both ESs over a complete market day;
- A long-term perspective where it is possible to understand the evolution of these SR characteristics over the complete period of analysis, developed on a quarterly (trimestral) basis.

In the Portuguese SR, the secondary upward regulation (SUR) quantity is considerably bigger than the secondary downward regulation (SDR), by about 6 times. Compared to the SES, it has a relative equilibrium in the secondary mobilizations.

Table 3
Secondary and Tertiary Energy Mobilization between the Iberian TSOs.

Secondary Control (GWh)	2015		2016	
	Upward	Downward	Upward	Downward
Portugal	425	68	439	81
Spain	1366	1193	1530	1012
Tertiary Control (GWh)				
Portugal	693	1269	1154	1284
Spain	3126	1627	2557	1553

Table 4
Secondary and Tertiary Energy Mobilization Prices between the Iberian TSOs.

Secondary Control (€/MWh)	2015		2016	
	Upward	Downward	Upward	Downward
Portugal	68.20	29.00	54.00	22.80
Spain	53.70	38.50	43.00	32.40
Tertiary Control (€/MWh)				
Secondary Control	68.20	29.00	54.00	22.80
Tertiary Control	63.70	24.80	50.20	19.40
Band Price of the Secondary Control (€/MWh)				
Portugal	20.46		16.67	
Spain	19.58		15.56	

Two reasons that may help explain this phenomenon are related and correlated, i.e., the first one is that the rules in place, since the beginning of the electricity market, require SR providers to offer a band of reserve which is split according to a ratio of 2/3 for upward and 1/3 for downward regulation, respectively.

At the same time, the TSO, which is mostly focused on the technical conditions of the system, tries to have the secondary band centered at the midpoint, i.e., with an equal amount of upward and downward regulation availability.

The second phenomenon is because the SR is mobilized automatically by the Automatic Generation Control (AGC), so the TSO indirectly controls the secondary band by manually dispatching RR, and thus, forcing the AGC to adjust the SR in the intended direction. In this sense, the latest explanations may help to understand why in the PES more energy is mobilized to downward regulation in order to maintain the equilibrium point.

In terms of electricity prices, in the PES the secondary control used is paid at the same price as the tertiary mobilization energy. Hence, the SES has an independent system of electricity prices. Comparing the prices of secondary mobilizations in the Iberian countries, the Spanish system is more competitive in both directions: it is cheaper to mobilize in the upward and downward directions, and the same happens for RR control.

The existence of more players in the SES, in the generation sector, may justify this situation. In terms of band price, in €/MWh, the same trend is verified in SR and in RR. However, the difference is very small.

3.1. Daily market analysis

Fig. 1 shows the average net mobilization of both ESs during the 24 h of a market day. The net value is obtained by subtracting the downward value from the upward reserve.

The average value of the net mobilization in the PES is 40.7 MWh, and in the SES is 39.4 MWh. The absolute value is very similar, and the Spanish TSO is 5 times bigger (as it was described previously). From the Portuguese TSO, during 2015 and 2016, the average secondary band offered in the market was 170 MW for upward regulation and 85 MW for downward regulation. The total band was thus, on average, 255 MW, having an equilibrium midpoint of 42.5 MW. This value is very similar to 40.7 MWh, which is the period analysis average value.

Comparing the previous values with the values in Table 4, for the Portuguese TSO, the net secondary control in 2015 was 425 − 68 = 357 GWh, and in 2016 it was 439 − 81 = 358 GWh, corroborating the results shown in Table 4. Another explanation for this fact is that it is a strict, stable and positive dominance of the secondary allocation to upward regulation which corresponds to 200% of the downward regulation. The oscillation verified is situated between 17 MW and 59 MW.

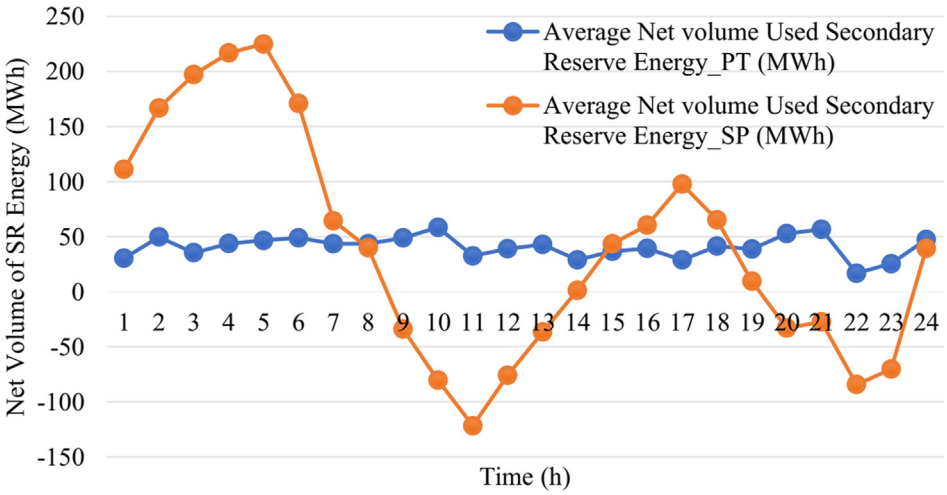
Average Net volume Used Secondary Reserve Energy_PT (MWh)
Average Net volume Used Secondary Reserve Energy_SP (MWh)
Net Volume of SR Energy (MWh)
Time (h)
250
200
150
100
50
0
-50
-100
-150
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Fig. 1. Average net volume used on the SR with Iberian TSOs.

In terms of the SES, it is 39.4 MWh (as mentioned previously). For the Spanish TSO, during 2015 and 2016, the average secondary band offered in the market for upward regulation was 683.5 MW, and for downward regulation it was 510 MW. The total band was thus, on average, 1193.5 MW, which has an equilibrium midpoint of 86.7 MW. When compared to the Portuguese TSO, in absolute terms, it approximately doubles its value (42.5–86.7 MW), but in relative terms, the difference is not so high (the Spanish system is 5 times bigger, with an equivalent midpoint at 86.7 MW/5 = 17.4 MW in the "Portuguese scale").

The difference between the allocation band for upward and downward regulation is 173.5 MW, which corresponds to 25% more upward allocation than downward allocation. This may help to explain a bigger volatility in the secondary band of the Spanish system, in comparison with the Portuguese one.

Again, comparing these with the values in Table 4, the net secondary control in 2015 was of 1366 − 1193 = 173 GWh, and in 2016 it was of 1530 − 1012 = 518 GWh, corresponding to an average value of 345.5 GWh, corroborating the results shown in Table 4. Fig. 2 shows the ratio between secondary utilization and secondary available band for upward and downward regulation, in both TSOs.

In the case of SUR, the average ratio of utilization for the Portuguese TSO is 29%, and in the case of SDR it is 10%. For the Spanish TSO, the average ratio of utilization is 25% in the case of SUR, and 24% for SDR. The first deduction is that the SES has a more balanced utilization of its resources. In the Portuguese TSO, the utilization of SDR is considerably low. In a first and localized analysis, when confronted with Fig. 1, Table 4, and with the allocation ratios of 2/3 for upward regulation and 1/3 for downward regulation, it is revealed that it is not necessary to contract more secondary downward band and it is necessary contract more upward band.

Nevertheless, it is important to take into account that the tertiary downward regulation (TDR) is considerably high. The coordination between these two mechanisms is responsible for the downward balance. Hence, considering the tertiary downward regulation, in Table 4, it is possible to observe that it is considerably mobilized when compared with the SDR. The PES has certain idiosyncrasies that help to explain this imbalance between the SUR, SDR and tertiary regulation systems. One of the reasons is the dimension of the PES when compared to the SES.

The PES's scale helps to maintain more stability. Another important reason is the existence of two main consumers in the PES: the national steel industries, which together totalized a peak power consumption of, approximately, 350 MW.

Another characteristic of the Portuguese steel industry is its profile consumption. It is a highly intensive energy industry (more than 90% of the costs are related to electricity), with the electric arc furnace working in step mode. For an ES such as the Portuguese one, the secondary control band cannot cover all variation scenarios (the average value of total band is 255 MWh), especially in scenarios when the steel

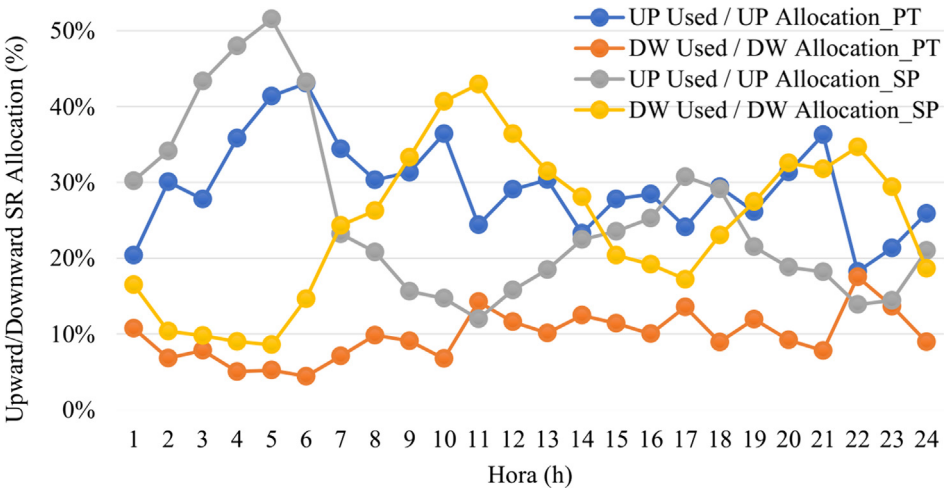
UP Used / UP Allocation_PT
DW Used / DW Allocation_PT
UP Used / UP Allocation_SP
DW Used / DW Allocation_SP
Upward/Downward SR Allocation (%)
Hora (h)
50%
40%
30%
20%
10%
0%
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Fig. 2. Upward and Downward SR allocation between the Iberian TSOs.

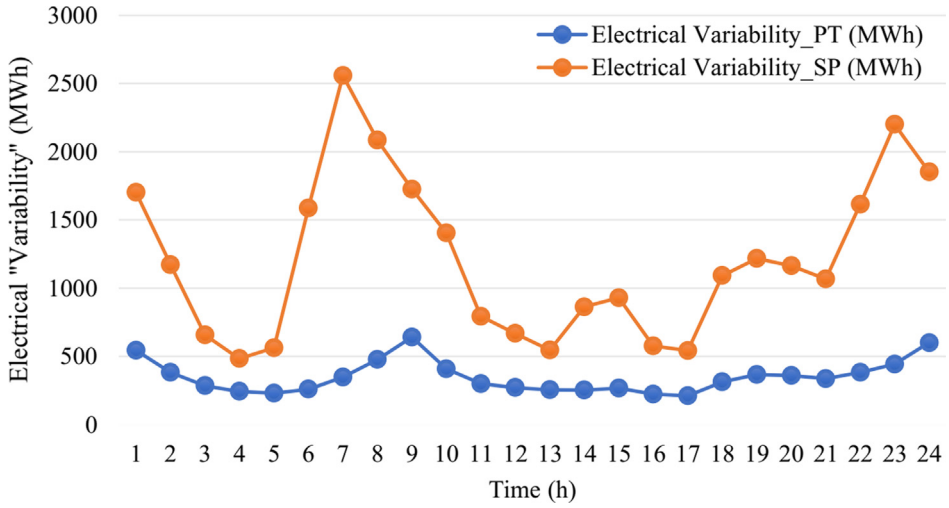

Fig. 3. "*Electrical variability*" between the Iberian TSOs.

industries stop and start working, but truly mainly when the steel industries start and stop instantly, because the downward secondary control band is 1/3 of the total band.

The Portuguese system operator (PSO), during the periods when the steel industries are working, creates an artificial imbalance with TDR in order to maximize the SDR. It is important to note that the secondary band is faster when controlling the deviation than the tertiary control band is. Another situation is that the steel industry usually works with more intensity during the night, when the consumption levels decrease. This is another reason why the PSO needs to anticipate for the "loss" of consumption. This idiosyncrasy helps to explain the secondary results observed for the PES.

Fig. 3 shows the "*electrical variability*" of both IES's in absolute values (MWh). It is a measure that intends to assess the main factors that incite entropy and fluctuations during a particular period in the IES and that must be corrected with a first action of the secondary control ("unpredictability" factors), where the average of the "*electrical variability*" in a market day is also shown.

The factors that incite a certain instability for the period h are the variation of production Δ_{Prod}, the variation of consumption Δ_{Con}, and the variation of interconnection Δ_{Inter}, described by the electrical variation EV in MWh:

$$EV\,(MWh)_h = abs(\Delta_{Prod\,h} - \Delta_{Load\,h}) + \Delta_{Inter\,h} \quad (1)$$

where the first term is the absolute value difference between the programmed generation variation and the load variation. The programmed generation variation is the producers' imbalance market indicator (the real production $Prod_{effective}$, minus the production market sold $Prod_{market}$).

This producer market imbalance is mostly related to the imbalance of the wind producers. Concerning the other dispatchable generation, typically, when losing one generator, typically, the producer has some mechanisms (as other power plants, for instance) to compensate the loss of the unit with other means of production, in order to reduce the imbalance. This is explained as:

$$\Delta_{Prod\,h} = Prod_{efective_h} - Prod_{market\,h} \quad (2)$$

In terms of the variation of consumption Δ_{Load}, it is the value of the difference between the level of consumption at the end, and at the beginning of the market period h:

$$\Delta_{Load\,h} = Load_{h(minute\ \ 0)} - Load_{h(minute\ \ 59)} \quad (3)$$

Moreover, focusing on the interconnection Δ_{Inter}, for the different market periods (in MIBEL it is the hour step), different interconnection programs could be take place between TSOs. The variation of interconnection is given by the expression:

$$\Delta_{Inter\,h} = (abs(Inter_h - Inter_{h-1})/12) + (abs(Inter_{h+1} - Inter_h)/12) \quad (4)$$

The transition between different periods is not processed in a step mode. The transition from the period h to the period $h + 1$ is given by a ramp that starts in the last 5 min of the period h with the interconnection value of h, and finishes in the 5th minute with the interconnection value of the period $h + 1$.

In other words, it is a ramp with 10 min that corresponds to 1/6 of the market period. For each market period h, the first 5 min are used to adapt to the energy interconnection program of the period h, and the last 5 min of the market period h are used to adapt to the energy interconnection program of the period $h + 1$.

The variation of the interconnection for each period h is the sum of the difference between the interconnection value in the market period $h - 1$ and h divided by 12 (which corresponds to the share of the interconnection program of the period $h - 5$ minutes) with the difference between the interconnection value in the market period h and $h + 1$ divided by 12.

The concept of "*electrical variability*" is crucial to define the "internal instability" of an ES as well as to quantify the SR control that a specific TSO needs to ensure the reliability of its operation. In Fig. 4, it is possible to observe the relative value of "*electrical variability*", divided by the secondary total band.

As the state-of-the-art demonstrates, the SR is able to effectively correct the load variations, which is directly linked to the variability under analysis, and within the period that it is necessary to take an action to correct the deviation, thus dividing the SR by the available band. In the case of an enduring or critical lack in the requested SR balancing, this is solved through the mobilization of the RR, which starts its operation by means of a formal request to the producer and not automatically like the SR, or aFRR, and therefore, the necessary time for the assertive corrections will be higher [29].

When the "*electrical variability*" is attended, in relative terms, for both Iberian countries, it is possible to observe some interesting results: instead of the Spanish TSO having more absolute "*electrical variability*", in more than 90% of the market hours during the time range in analysis, the Portuguese TSO is subject to an "*electrical variability*" in relative terms.

Only in the periods 6 and 7, the Spanish TSO has more relative "*electrical variability*". In the period 23, the values are very similar (however, superior for the Portuguese TSO). The periods 6 and 7 represent the end of the beginning of the load growth for the SES, however for the PES it represents the end of the off-peak values.

This phenomenon is due to the different time zones, i.e., while in

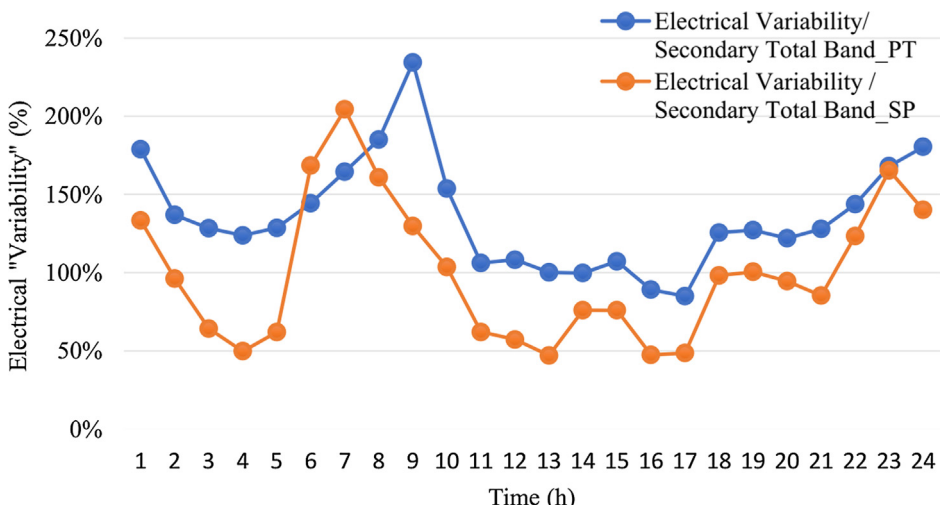

Fig. 4. Relative value of "*electrical variability*" divided by the secondary total band between the Iberian TSOs.

Spain the time zone is the Central European Time, in Portugal the time zone is the Western European Time. The average value of "*electrical variability*" for the Spanish TSO is 100%, and for the Portuguese TSO it is 134%. The assessment of "*electrical variability*" in relative terms gives more effective information about the internal entropy that a TSO is subject to, and also, allows an adequate comparison between the different TSO's.

3.2. Trimester analysis

In this section the main goal is to trace the evolution during the time of the measurements obtained in order to provide eventual trends. In Fig. 5, it is possible to observe a similar behavior as in Fig. 1, but it is possible to notice some differences, mainly for the Spanish TSO.

In the first and second quarters of each year, (which essentially corresponds to the winter and spring seasons in Europe), the Spanish TSO has a net volume of the secondary band used (the quantity of SUR is higher than SDR). On the contrary, in the third and fourth quarters (summer and fall seasons) the net volume used is near zero (or even negative), which means that SUR and SDR are more balanced.

In Fig. 6 it is possible to note the prices for SUR and SDR prices of the SR for both TSOs. The first and second quarters (winter and spring seasons) of both years under analysis, in both TSOs, have lower prices than the third and fourth quarters (summer and fall seasons). It is a predictable result because in both ESs there are a considerable amount of hydro power plants. The rainy periods are mainly during winter and the beginning of spring, so it is natural to have a general decrease in the electricity prices, in their most varied dimensions (spot, tertiary, secondary).

Moreover, it is possible to observe from Fig. 6 that the first and second quarters of 2016 have a lower price than same period in 2015. The main reason is due to the fact that in the Iberian Peninsula the year 2015 was a "dry" year, with less rain than normal, and 2016 was a "wet" year, with a considerable amount of rain for that period.

Fig. 7 shows the "*electrical variability*" during the eight quarter periods under the analysis. The average value of "*electrical variability*" for the Spanish TSO is 1200 MWh, and for the Portuguese TSO it is 350 MWh.

During the time range in analysis it is possible to observe more stability of the "*electrical variability*" in the PES than in the SES. An interesting observation is the fact that, in both TSOs, and in both years, the first quarter was the period when the "*electrical variability*" was higher.

This may happen because it is the beginning of the rainy period, which precipitates a certain level of entropy with an increase of the interconnection programs (with more exportation), and of the production. Also, in this quarter, the peak load takes place.

In Fig. 8, when divided by the secondary available band, it is possible to observe that the "*electrical variability*" is lower, in relative terms, for the second and third quarters of the years under analysis. Fig. 8 is the equivalent to Fig. 4, the differences is that the former presents a long-term perspective. It is possible to observe that, in relative terms,

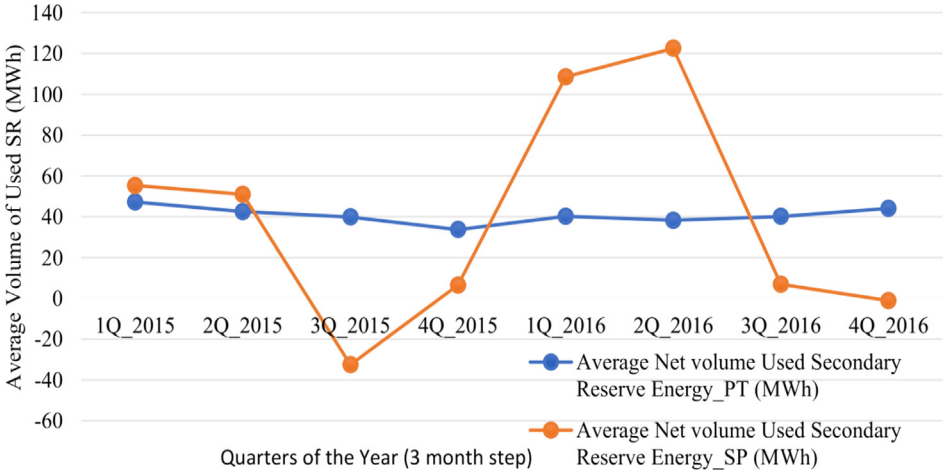

Fig. 5. Average volume of used of SR between the Iberian TSOs.

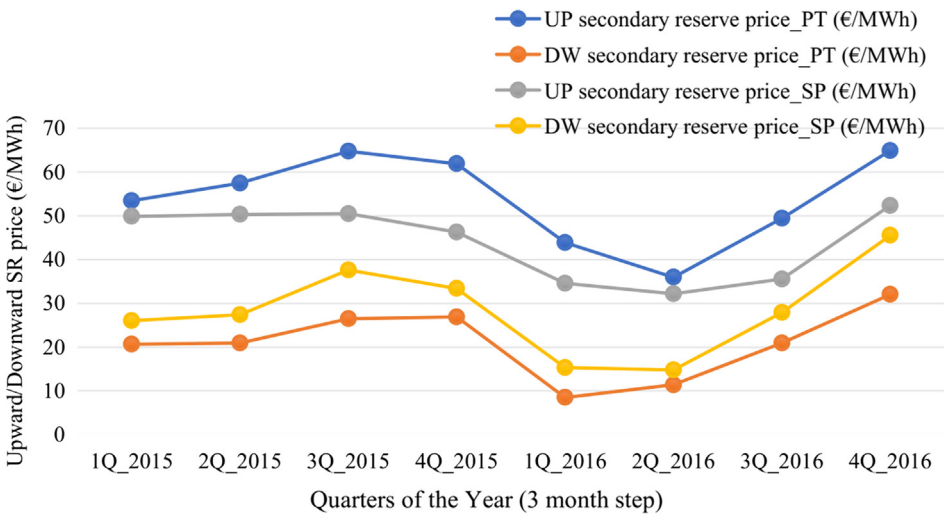

Fig. 6. Upward and downward SR prices practiced by the Iberian TSOs.

the Portuguese TSO is subjected to a higher *electrical variability* when compared to the Spanish TSO.

4. Identification and analysis of the potential Iberian TSO synergies

In this section, the possibility of synergies generated if both Iberian TSOs cooperate with the sharing of imbalance control, by the possibility of minimizing energy mobilization, will be analyzed. The way of cooperation between TSOs could be done by multiple mechanisms, methodologies and processes.

The chosen way for analyzing the possible cooperation is one where the model used does not request the sharing between TSOs of a considerable amount of information that could be classified as confidential by each TSO, like the prices or market agents. More efficient and complex ways of cooperation are possible, but it is necessary to share a considerable amount of information, that in normal situations the TSOs have some reluctance to share in real-time.

The major hindrance in the present analysis is the existence of hourly data instead of quarter-hourly data or smaller periods, which would give more precise results to our analysis. The existence of smaller periods would certainly increase the periods of cooperation. However, for the PES, the data in time-steps smaller than the hourly period is not available, and to this end, for coherence and fair analysis, the hourly data for both TSOs was implemented and analyzed.

The methodology used has two steps of analysis. In a first step, it compares only the direction of both AGCs. If both ESs have positive or negative imbalances, any possibility of cooperation is possible. However, in a second step, if one of the electrical systems has a positive imbalance and the other system has a negative one, there is a sole opportunity of cooperation.

The value of the imbalance is traded between TSOs and a subtraction is made, i.e., the value of the positive imbalance minus the value of the negative imbalance. If the remaining imbalance result is positive, the TSO who needs to activate SDR will decrease this new imbalance value. However, if the remaining imbalance result is negative, the TSO who needs to increase the SUR remains imbalance.

In other words, e.g., if the SES has 40 MW of positive imbalance and PES has 20 MW of negative imbalance, in reality, the Spanish SDR will decrease 40 MW and the Portuguese SUR will increase 20 MW.

However, this work's proposal intends to minimize the control executed by the Iberian TSOs, and considering the previous example, it is suggested to decrease the Spanish SDR by 20 MW, and the Portuguese SR will not be activated, so the Iberian system is, at this period, balanced.

A similar mechanism could be implemented in Europe as a whole, because the main objective is to maintain the EEG balanced. In this sense, the current work intends to analyze the possibility of cooperation at a regional level (from the Iberian electrical grid perspective), quantifying the periods and the amount of energy that could be involved, and analyzing in a second step the savings for both electrical systems with the suggested cooperative association. In brief, the proposed

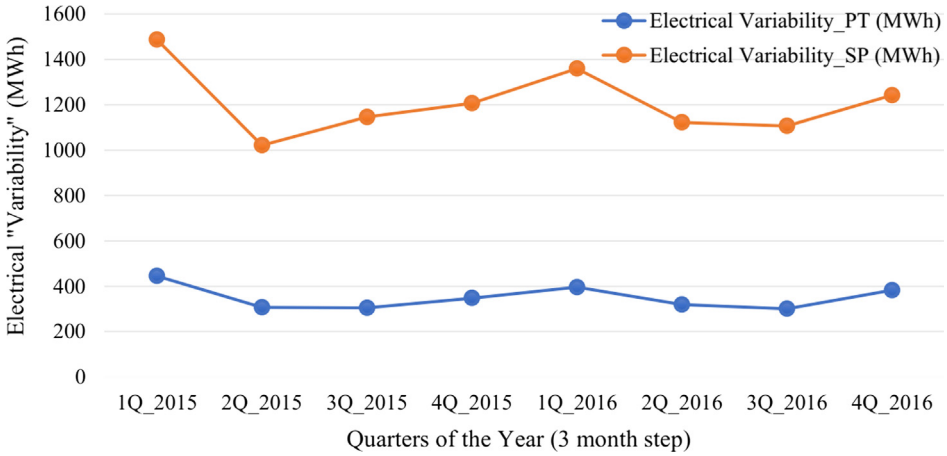

Fig. 7. "*Electrical variability*" comparison behavior between the Iberian TSOs.

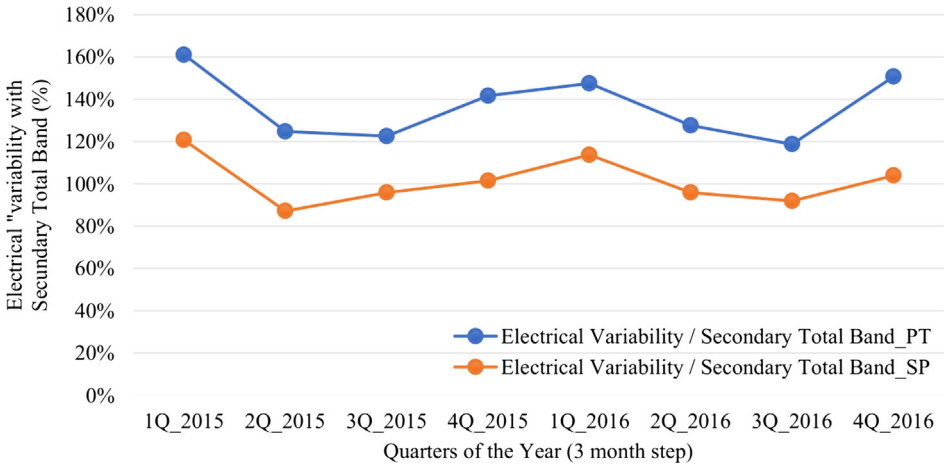

Fig. 8. "*Electrical variability*" through the secondary total band between the Iberian TSOs.

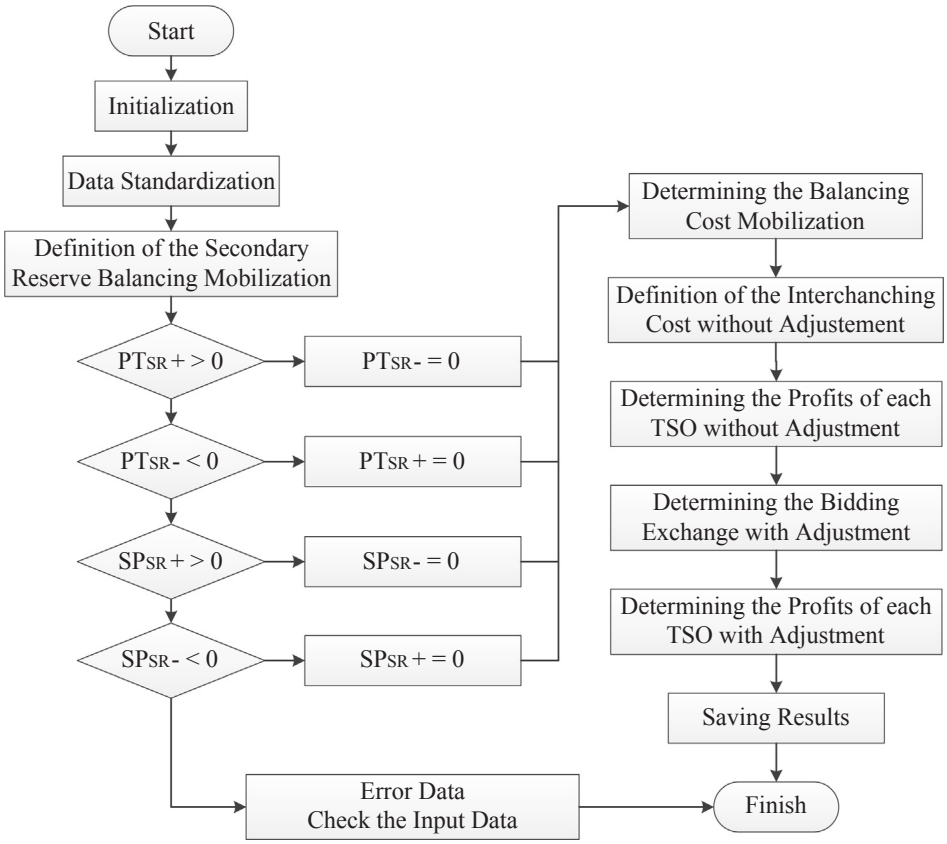

Fig. 9. Techno-economic flowchart with TSOs synergies analysis between Portugal (PT) and Spain (SP).

techno-economic analysis and expected synergies between Iberian TSOs is summarized in Fig. 9.

Like in the previous sections, in this section a more detailed analysis will be done, focused exclusively on the possible synergies between both Iberian TSOs, arranging the results in a specific manner that enables two different types of reflections:

- A daily analysis (a short-term perspective) where it will be possible to understand the possibility of synergies between the TSOs in a market day;
- A more long-term perspective where it will be possible to understand the evolution of the possible exchanges over the complete period of analysis, carried out in a quarterly (trimestral) basis.

4.1. Mathematical formulation

As explained in previous sections, the Iberian TSOs exchange the actual imbalance capacity in their control areas through an individual optimization model. Optimizing the shared SR synergy between each TSO can only run if the optimization SR in each electrical grid has been completely used.

The needless SR energy is exchanged through the following rule: the TSO with more SR energy on its own control area supplies to the control area with lower SR energy. In this sense, a reduction in SR energy needs may occur in each TSO, and consequently the need of SR energy is mitigated by considering the remaining demand. So, the main goal of sharing the SR between the Iberian TSOs is to fairly split-up the savings made through the prevented use of SR energy between the TSOs [30].

To this end, it is necessary to first define the interchanging SR cost between the Iberian TSOs considering a sharing synergy framework. Accordingly:

$$TISRE_h = \sum_{h=1}^{H} ((ISRE_{PTh} \times SMPD_{PTh}) + (ISRE_{SPh} \times SMPD_{SPh})) \quad (5)$$

where $TISRE_h$ is the total imported SR energy at time h; $ISRE_{PTh}$ is the imported SR energy from the Portuguese TSO at time h; $SMPD_{PTh}$ is the SDR market price asked to the Portuguese TSO at time h; $ISRE_{SPh}$ is the imported SR energy from the Spanish TSO at time h; $SMPD_{SPh}$ is the SDR market price asked to the Spanish TSO at time h.

Considering the same idea about the exported SR energy, the information can be expressed as:

$$TESRE_h = \sum_{h=1}^{H} ((ESRE_{PTh} \times SMPU_{PTh}) + (ESRE_{SPh} \times SMPU_{SPh})) \quad (6)$$

where $TESRE_h$ is the total exported SR energy at time h; $ESRE_{PTh}$ is the exported SR energy from the Portuguese TSO at time h; $SMPU_{PTh}$ is the SUR market price asked to the Portuguese TSO at time h; $ESRE_{SPh}$ is the exported SR energy from the Spanish TSO at time h; $SMPU_{SPh}$ is the SUR market price asked to the Spanish TSO at time h.

The total SR transacted between the Iberian TSOs is expressed as:

$$TSRG_h = \sum_{h=1}^{H} (ISRE_{PTh} + ISRE_{SPh}) + \sum_{h=1}^{H} (ESRE_{PTh} + ESRE_{SPh}) \quad (7)$$

So, the costs of the sharing SR between the Iberian TSOs and the resulting payments or benefits without adjustments are expressed as:

$$CIGCC_h = (TISRE_h + TESRE_h)/TSRG_h \quad (8)$$

where $CIGCC_h$ is the cost of the Iberian grid control cooperation at time h, and:

$$MIGCC_{PT} = (ISRE_{PTh} - ESRE_{PTh}) \times CIGCC_h \quad (9)$$

$$MIGCC_{SP} = (ISRE_{SPh} - ESRE_{SPh}) \times CIGCC_h \quad (10)$$

And so, $MIGCC_{PT}$ and $MIGCC_{SP}$ represent the individual grid control cooperation costs from Portuguese and Spanish TSOs, respectively. Thus, the benefits for each TSO without adjustments are expressed as:

$$BGC_{PTh} = ((ISRE_{PTh} \times BCSDR_{PTh}) - (ESRE_{PTh} \times BCSUR_{PTh})) - MIGCC_{PT} \quad (11)$$

$$BGC_{SPh} = ((ISRE_{SPh} \times BCSDR_{SPh}) - (ESRE_{SPh} \times BCSUR_{SPh})) - MIGCC_{SP} \quad (12)$$

where $BCSDR_{PT_h}$ and $BCSDR_{SP_h}$ are the bidding costs of SDR for the Portuguese and Spanish TSOs, respectively; $BCSUR_{PTh}$ and $BCSUR_{SP_h}$ are the bidding costs of SUR for the Portuguese and Spanish TSOs, respectively. The group SR sharing, without adjustment, is given by:

$$BCGT_h = BGC_{PTh} + BGC_{SPh} \quad (13)$$

However, in order to increase the benefits and create reliable synergies between TSOs, the adjustments are required. To this end, the following steps are necessary for each Iberian TSO:

$$MIGCCA_{PT_h} = MIGCC_{PT_h} + BCG_{PTh}, \quad BCG_{PTh} < 0, \quad ISRE_{PTh} \neq ESRE_{PTh} \quad (14)$$

$$MIGCCA_{PT} = MIGCC_{PT_h} - \sum_{h=1}^{H} (\min(BCG_{PT}) \times (BCG_{PTh}/\max(BCG_{PT}))), \quad BCG_{PTh} > 0,\ ISRE_{PTh} \neq ESRE_{PTh} \quad (15)$$

$$MIGCCA_{SP_h} = MIGCC_{SP_h} + BCG_{SPh}, \quad BCG_{SPh} < 0, \quad ISRE_{SPh} \neq ESRE_{SPh} \quad (16)$$

$$MIGCCA_{SP_h} = MIGCC_{SPh} - \sum_{h=1}^{H} (\min(BCG_{SP}) \times (BCG_{SPh}/\max(BCG_{SP}))), \quad BCG_{SPh} > 0,\ ISRE_{SPh} \neq ESRE_{SPh} \quad (17)$$

where $MIGCCA_{PT_h}$ and $MIGCCA_{SP_h}$ are the Iberian grid code cooperation between the Portuguese and Spanish TSOs, respectively. The benefits with adjustment, for each TSO are given by:

$$BIGCC_{PTh} = ((ISRE_{PTh} \times BCSDR_{PTh}) - (ESRE_{PTh} \times BCSUR_{PTh})) - MIGCCA_{PT_h} \quad (18)$$

$$BIGCC_{SPh} = ((ISRE_{SPh} \times BCSDR_{SP_h}) - (ESRE_{SPh} \times BCSUR_{SPh})) - MIGCCA_{SP_h} \quad (19)$$

The overall benefits, with adjustments, between the Iberian TSOs when sharing SR are:

$$BICGAT_h = BIGCC_{PTh} + BIGCC_{SPh} \quad (20)$$

4.2. Daily market analysis through Iberian TSO synergies

In Fig. 10 it is possible to observe the periods, according to the adopted mechanism, where the synergies could occur. The average value of synergies between TSOs occurs in 45% of the periods. The synergies occurred with more frequency in the peak periods and during the load increases. In the off-peak periods, the synergies decrease significantly. This is an expected result because the similar time zone due to the geographic proximity makes the load behavior very similar in

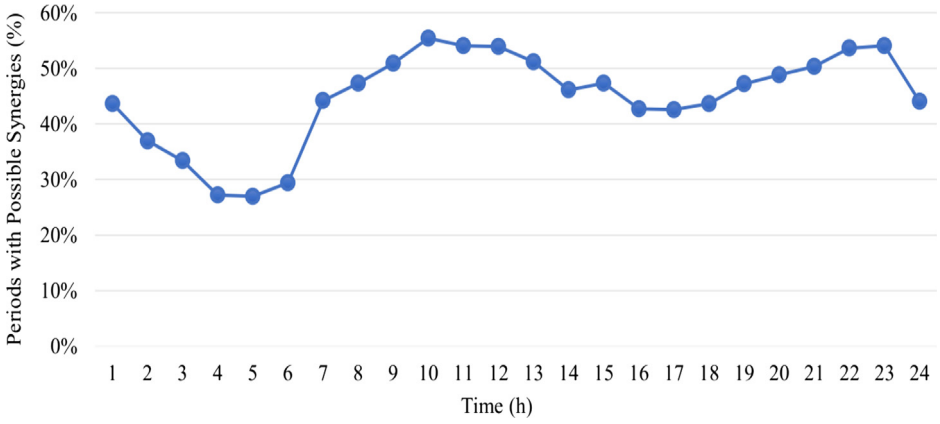

Fig. 10. Periods of possible SR synergy between the Iberian TSOs.

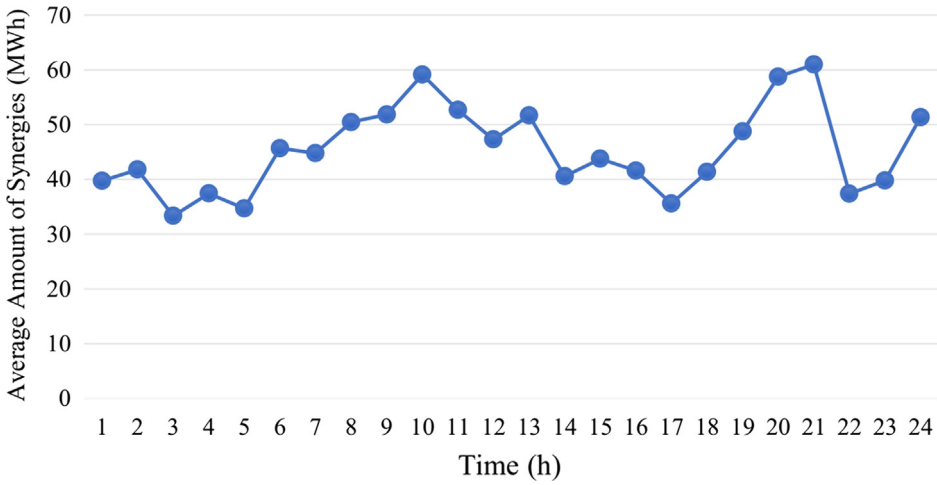

Fig. 11. Average amount of SR synergy between the Iberian TSOs.

both countries.

Considering to the absolute average value of the Iberian TSO synergy, in off-peak periods this value is lower than average. The reasons are related to those previously described. For such reasons, in off-peak periods, as shown in Fig. 11, fewer transactions occurred, containing lower quantities. It is interesting to observe the behavior in periods 5, 6 and 7, respectively.

From Fig. 11, despite having similar time zones, the one-hour difference makes the load increase, because of the different waking up hours in both countries, generating more synergies during this period.

Moreover, in Fig. 12 it is possible to observe the average value of each synergy moment. The results are in accordance with the previous observations, i.e., the average value of synergy between the TSOs is lower in off-peak periods. However, when a certain degree of stability in the load periods is observed, as is from 12 to 18, the price of the synergies tends to decrease. This trend could be associated with price similarity in different electrical systems.

The set of Figs. 10–12 corroborates that in off-peak periods the Iberian TSOs have fewer possibilities of synergy, less average value per synergy and less profit per synergy. These conditions are reflected and demonstrated in Fig. 13. From Fig. 13, it is possible observe the trend established in the Fig. 12. The decrease not only occurs in volume but also, considerably, in revenues between periods 12–18.

4.3. Trimester analysis considering the Iberian TSO synergies

In this section, the possible Iberian TSO synergies are analyzed in a time evolutionary perspective, in order to understand the seasonal behaviors. In Fig. 14 it is possible to observe the percentage of periods when the synergies are possible. It is possible to verify a considerable stability, whereas in Fig. 11 some oscillations are observed. The possibilities of synergy slightly diminish in the first and second quarters of both years under analysis.

By comparing Fig. 7 and the respective Fig. 14, in the period under analysis, in both ESs, it can see that the hydro power plants have more capacity to produce and the energy available in both systems is higher, making the energy price, and the associated services decrease on both sides, and consequently, it makes the synergy possibility less attractive.

Due to similarities and geographical proximity, as well as to a mix in energy production from both TSOs, it is natural to observe a certain degree of stability in the periods when the synergies occur.

Fig. 15 shows the total amount of traded energy from each TSO in each quarter of the years under analysis. As observed, the traded energy does not have the same stability as seen in the percentage of periods when synergy between the Iberian TSOs occurred.

Moreover, in Fig. 16, it is possible to observe the total economic value of the synergies in each quarter of the years under analysis. In line with Fig. 15, it is possible to observe considerable variations. Hence, as observed and commented in Fig. 6, the periods when it is possible to have more profits are the summer and the fall seasons, considering the reasons previously described.

4.4. General results from the Iberian TSO synergy analysis

In this section, the main goal is to analyze the general results of the Iberian TSO synergies in the aFRR. Considering the synergy

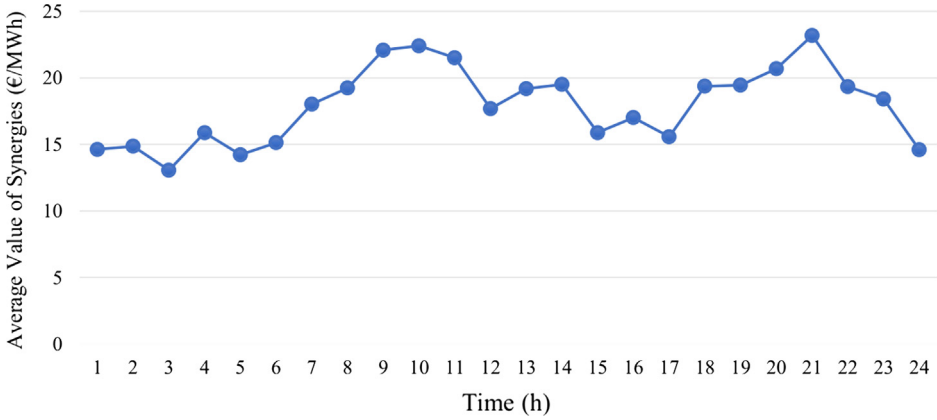

Fig. 12. Average price value of synergy occurred between the Iberian TSOs.

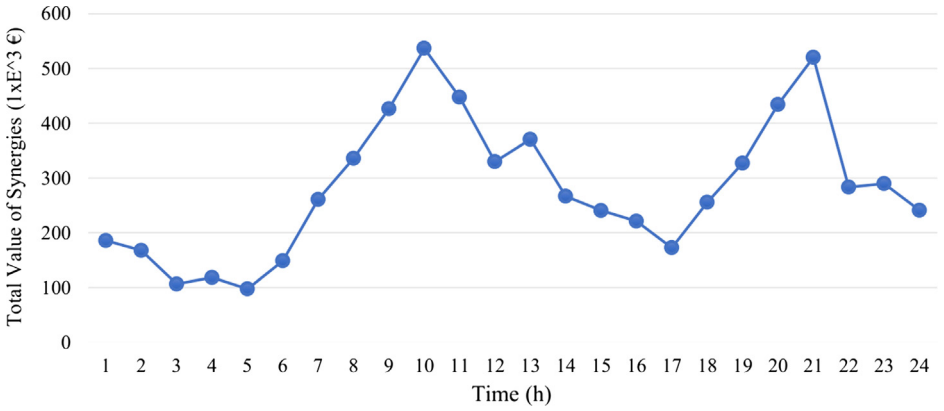

Fig. 13. Total value of synergy analysis between the Iberian TSOs.

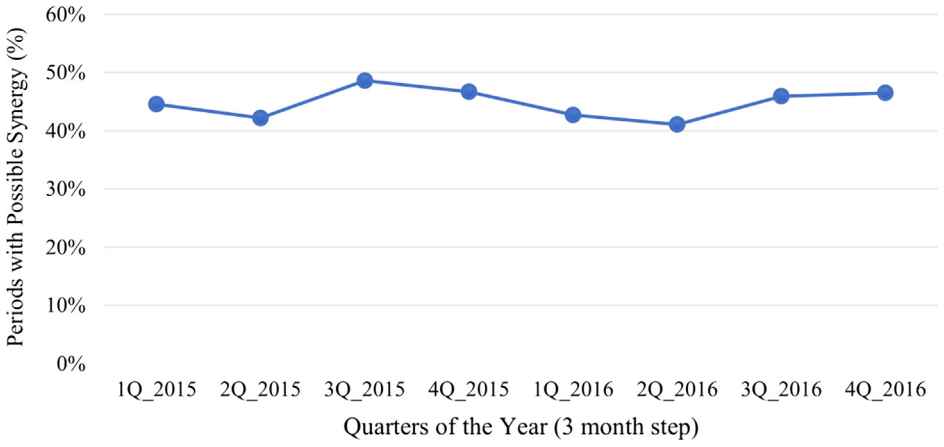

Fig. 14. Periods of possible synergy analysis between the Iberian TSOs.

occurrences, with the adopted method described previously, it became possible for Iberian TSOs to cooperate in approximately 45% of the time periods. The yearly difference corresponds to only 1.4%, which is not a significant difference.

The same happened with the energy that the Iberian TSOs could avoid to mobilize. It is the sinergy's energy. The quantity of synergy decreased 7.5% when comparing 2016 (189 GWh) to 2015 (175 GWh), where not only the periods of possible synergy decreased but also the quantity of synergy was higher in the beginning. One of the main reasons for these decreases is related to the "wet" winter registered in 2016, in comparison with the same period of 2015.

As previously described, both ESs are considerably exposed to the hydro power production, with a considerable amount of water on both sides of the borders. That means that there is more available energy on both ESs. This fact has a direct impact on electricity price (which decreases) and an indirect impact on other services such as tertiary or SR control. In term of the potential value of savings, the same occurred with the quantity of energy. The prices' reduction originates a lower potential for savings, with a decrease of, approximately, 12.5% when comparing the year 2016 (3.62 M€) to 2015 (3.16 M€). Table 5 summarizes the results explained here.

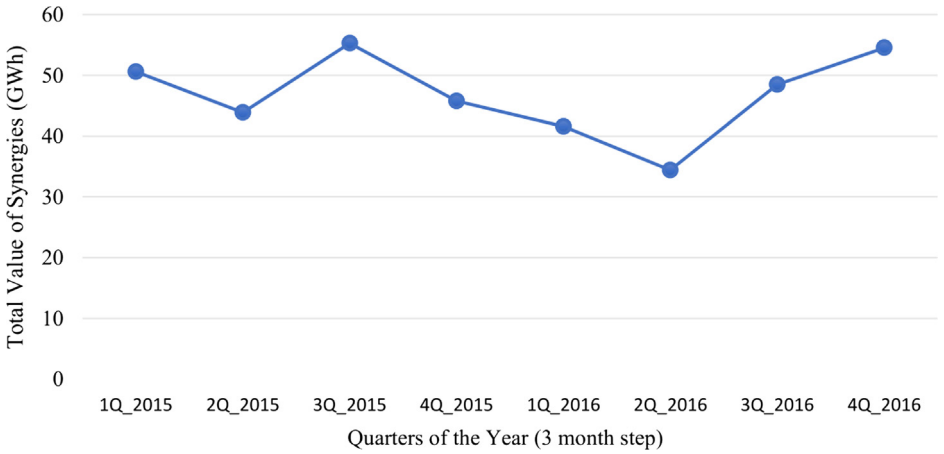

Fig. 15. Total value of synergy transacted between the Iberian TSOs.

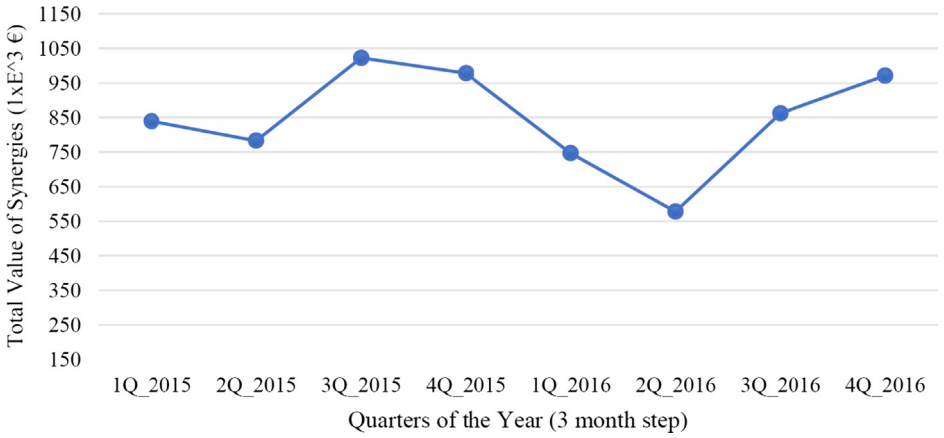

Fig. 16. Total value of benefits synergy transacted between the Iberian TSOs.

Table 5
Iberian TSO synergies.

	2015	2016
Sinergy Periods (hours)	3988	3871
Percentage of Synergy Periods	45.50	44.10
Quantity of Sinergy Transacted (GWh)	189	175
Total Value of Synergy Benefits (Millions of €)	3.62	3.16

5. Conclusions

The EEG is one of the biggest interconnected systems in the world. Twenty-four TSOs make up this huge grid, which composes the ENTSO-E electrical system, with the main goal of operating in a secure and reliable way to supply the load. With the growth of electrical markets in the most varied dimensions, the traded energy became an intensive reality, not only in the spot markets, but also in the AS.

The capital importance of AS in the ESs, so ESs can operate with security, is undeniable. In the last decade, these ES's strengthening of sharing became a reality, not only by market developments but by the considerable increase of renewable generation in the EEG, mainly wind and solar. The reduction of pollutant emission rates was one of the main gains from the use of these new technologies to produce electricity.

However, new challenges came up in the operation of ESs. These new ways to produce electricity scattered and with more or less expression in all of Europe, have a certain degree of intermittency that forces system operators to adapt to such fluctuations and to a certain degree of production instability. To this end, one of the measures was the increase of the AS, in particular the aFRR. However, the increment of the aFRR in the market environment (the reality across the ENTSO-E sphere) increases the overall costs.

The main goals for the TSOs in EEG sphere are to maintain the ES reliable and to supply the consumers at lowest possible costs. With a European interconnected grid, it does not make sense for TSOs to think only in term of their own territory. An electrical incident in one TSO could generate a partial or even a total blackout in its neighborhoods.

It is worthless to keep the ES balanced if a problem may arise in the nearest TSO. In certain circumstances, maintaining the system imbalanced could help to maintain the frequency in adequate levels, avoiding global and major problems. This can be an adequate measure to improve the reliability of ESs, and to reduce the costs for the providers of AS, proven that an adequate coordination between TSOs is carried out.

For TSOs that share the same geographical space, as the Iberian ones, the main goal is to maintain this regional area balanced. To maintain the region balanced, at the lowest possible cost, a constant and adequate coordination must be provided. Historically, to keep the region balanced, each TSO takes care of its own internal imbalance.

The present work showed that it is possible to maintain the region's balance with both TSOs imbalanced, reducing the costs with the operating reserves. In economic terms, the possibility of synergies in, approximately, 45% of the market periods, generates global savings around 3.4 M€. The sharing of aFRR in a regional, or even continental context, has multiple advantages, among them, the techno-economic features studied in this wok.

Acknowledgements

J.P.S. Catalão acknowledges the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under SAICT-PAC/0004/2015 (POCI-01-0145-FEDER-016434), 02/SAICT/2017 (POCI-01-0145-FEDER-029803) and UID/EEA/50014/2019 (POCI-01-0145-FEDER-006961).

Disclaimer

The views expressed in this work are those of the Authors and do not necessarily represent those of REN or any company belonging to REN.

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